Minimum Bias and MC Tuning at LHCb

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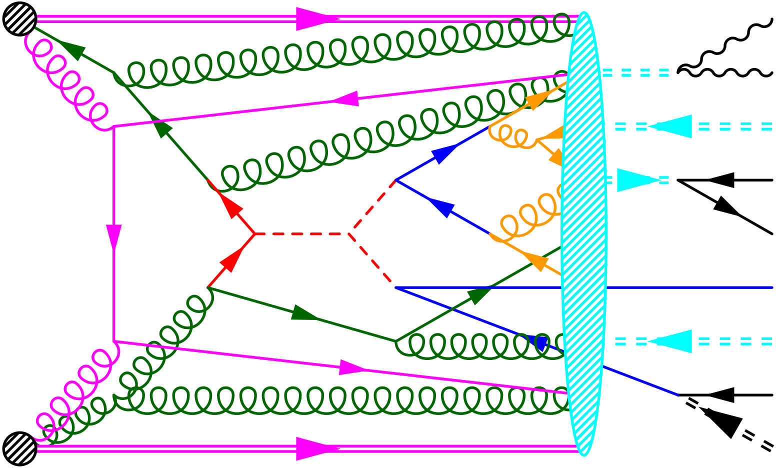
11th International Workshop on Multiple Partonic Interactions at the LHC

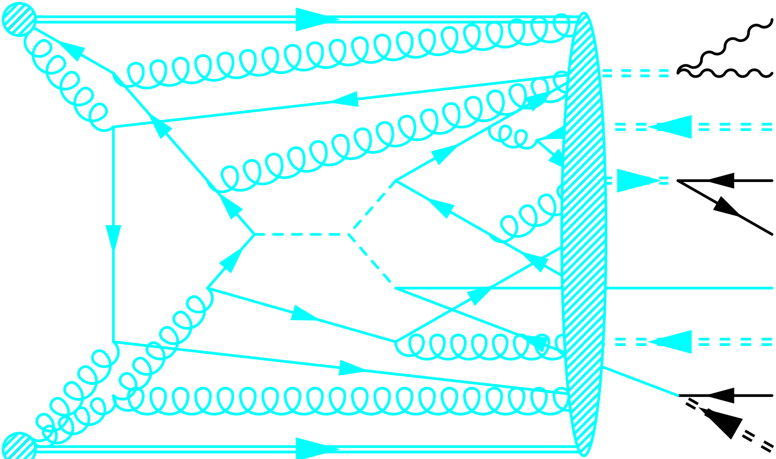
Event Anatomy

1) hard process
2) resonance decays
3) ISR
4) FSR
5) underlying event
6) hadronization
7) particle decays



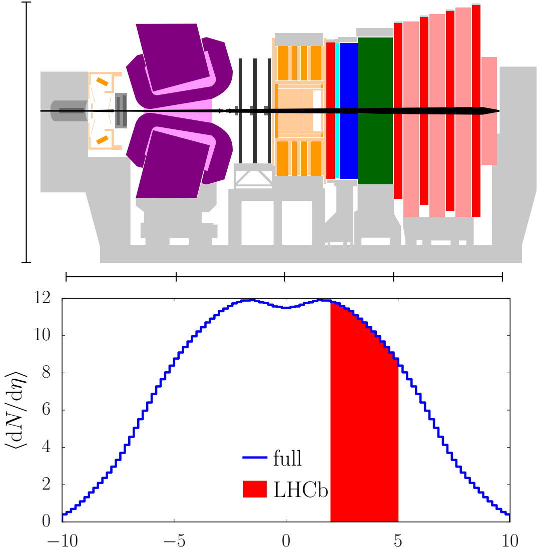
LHCb Event Anatomy

1) production 2) particle decays



LHCb Acceptance

[JINST 3 (2008) S08005]



Tuning Parameters

[T. Sjöstrand]

- hard process
  - PDFs, phase space cut-offs ($\hat{p}_{\mathrm{T}}$, $\hat{m}$), renormalization scale, factorization scale, SM parameters (CKM, $\alpha_s(M_Z)$, $\sin\theta_W$)
- parton showers
  - $\alpha_s(M_Z)$, scales, p_{T} damping, matching parameters, ordering method
- underlying event
  - $\alpha_s(M_Z)$, hard processes, p_{T} damping, beam profile (shape, impact parameter), color reconnection
- hadronization
  - longitudinal momentum sharing, transverse width, flavor composition, vector to pseudo-scalar composition, baryon and meson production ratios

Observables

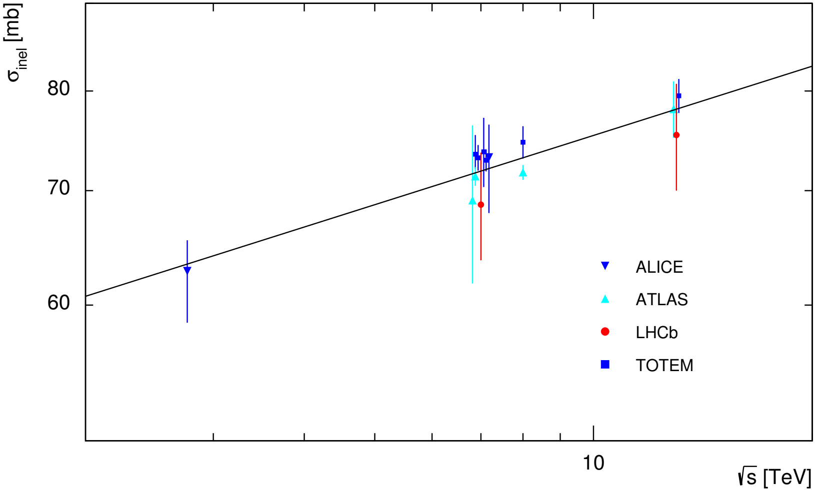
- test non-perturbative regimes of QCD
- tune multi purpose event generators
- look for new effects to refine models
- hard process
  - onia inclusive cross-sections
  - onia p_{T} distributions
- ISR
  - light jet thrust ($\alpha_s(M_Z)$)
  - p_{T} from $Z \to \mu\mu$ (primordial k_{T})
- FSR
  - similar to ISR
- underlying event
  - onia measurements
  - IR safe energy flow
- hadronization
  - final state flavor composition
  - IR sensitive charge density and multiplicity
- particle decays
  - branching fractions
  - mass distributions, angular distributions, etc.

LHCb Public Rivet Analyses

analysis	plugin	reference
inelastic cross-section	LHCB_2015_I1333223	JHEP 1502 (2015) 129
charge particle multiplicities and densities	LHCB_2014_I1281685	Eur. Phys. J. C 74 (2014) 2888
energy flow	LHCB_2013_I1208105	Eur. Phys. J. C 73 (2013) 2421
prompt charm cross-sections	LHCB_2013_I1218996	Nucl. Phys. B 871 (2013) 1-20
charged particle ratios	LHCB_2012_I1119400	Eur. Phys. J. C 72 (2012) 2168
V^0 ratios	LHCB_2011_I917009	Eur. Phys. J. C 72 (2012) 2168
inclusive ϕ cross-sections	LHCB_2011_I919315	Phys. Lett. B 703 (2011) 267-273
prompt K_S^0 cross-sections	LHCB_2010_S8758301	Phys. Lett. B 693 (2010) 69-80
inclusive $b\bar{b}$ cross-sections	LHCB_2010_I867355	Phys. Lett. B 694 (2010) 209-216

Inelastic Cross-Sections

[JHEP 06 (2018) 100]



Onia Production

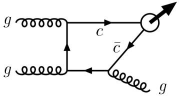
Production Model

[hep-ph/0003142]

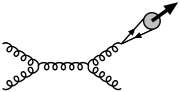
- onia production typically modeled with NRQCD

$$\mathrm{d}\sigma(pp \to H + X) = \sum_{s,L,J} \mathrm{d}\hat{\sigma}(pp \to Q\bar{Q}[^{2s+1}L_J] + x)\langle \mathcal{O}^H[^{2s+1}L_J]\rangle$$

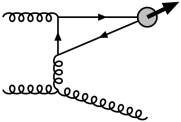
- physical state is expanded as Fock states



$gg \to c\bar{c}[^3S_1^{(1)}]g$



$gg \to c\bar{c}[^3S_1^{(8)}]g$



$gg \to c\bar{c}[^1S_0^{(8)}, ^3P_J^{(8)}]g$

p_T Damping

- perturbative short-distance matrix elements, $\hat{\sigma}$, diverge at low p_T
  - smoothly re-weight

$$\left(\frac{p_\mathrm{T}^4}{p_{\mathrm{T}0}^2 + p_\mathrm{T}^2}\right)\left(\frac{\alpha_s(p_{\mathrm{T}0}^2 + p_\mathrm{T}^2)^2}{\alpha_s(p_\mathrm{T}^2)}\right)$$

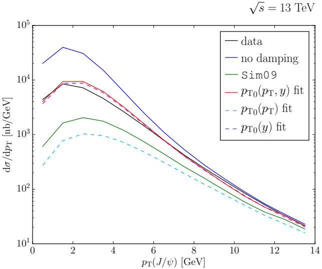
  - allow $p_{\mathrm{T}0}$ to be energy dependent

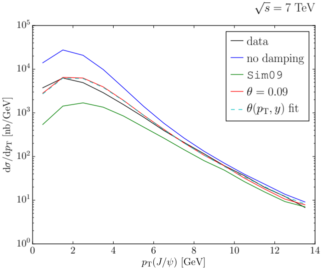
$$p_{\mathrm{T}0}(\sqrt{s}) = p_{\mathrm{T}0}(E_0)\left(\frac{\sqrt{s}}{E_0}\right)^{\theta}$$

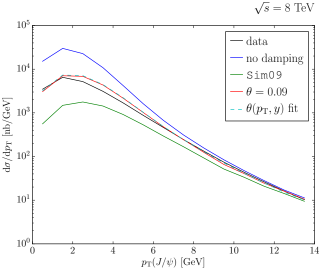
- fit LHCb data at various $\sqrt{s}$ to obtain both $p_{\mathrm{T}0}$ and θ

LHCb Damping

[JHEP 10 (2015) 172]







Energy Flow

Multi Parton Interaction Models

hard $\rightarrow$ soft model (HEP)	soft $\rightarrow$ hard model (air-shower)

- **begin with *t*-channel $2 \rightarrow 2$ QCD**

$$\mathrm{d}\hat{\sigma}_{2\rightarrow 2} \propto \mathrm{d}p_{\mathrm{T}}^2 \frac{\alpha_s^2(p_{\mathrm{T}}^2)}{p_{\mathrm{T}}^4}$$

- divergent in p_{T}, cut-off or damp

$$\frac{\alpha_s^2({p_{\mathrm{T}}}_0^2 + p_{\mathrm{T}}^2)}{\alpha_s^2(p_{\mathrm{T}}^2)} \frac{p_{\mathrm{T}}^4}{({p_{\mathrm{T}}}_0^2 + p_{\mathrm{T}}^2)^2}$$

- models color screening and saturation effects
- number of interactions also depends on impact parameter

$$f(x, b) = f(x)g(b)$$

- **begin with Regge effective field theory**

$$\mathrm{d}\sigma \propto \frac{\mathrm{d}M^2}{M^2}$$

- M is mass of the diffractive system
- exchange of color-singlet pomeron between hadrons
  - leading structure is $f\bar{f}$ or gg
  - at high energy primarily gg
- include hard structure by resolving pomeron constituents
- requires some smooth transition between the two regimes

LHCb Energy Flow Analysis

[Eur. Phys. J. C 73 (2013) 2421]

- measure charged energy flow
  - veto events with more than 1 primary vertex
  - use tracks with VELO and IT or OT hits
  - $2 < p < 1000$ GeV

$$\frac{1}{N}\frac{\mathrm{d}E}{\mathrm{d}\eta} = \frac{1}{\Delta\eta}\left(\frac{1}{N}\sum_{i=1}^{n(\Delta\eta)} E_i\right)$$

- $N \equiv$ number of inelastic pp interactions
- $n \equiv$ number of tracks within bin of $\Delta\eta$

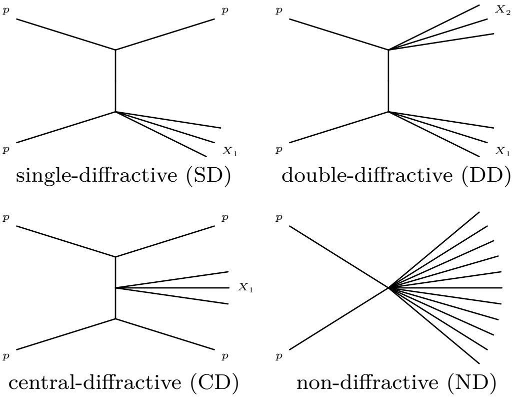
1. unfold detector effects with bin-to-bin corrections
   - estimate systematic uncertainty from model bias using various PYTHIA configurations
2. calculate total energy flow using neutral to charged ratio, R

$$F_{\text{total}} = F_{\text{charged}}(1 + R_{\text{gen}})\left(\frac{1 + R_{\text{data}}}{1 + R_{\text{MC}}}\right)$$

Event Classification

[Eur. Phys. J. C 73 (2013) 2421]

$$\sigma_{\text{inelastic}} = \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}} + \sigma_{\text{ND}}$$



hard

- $p_T > 3$ GeV
- $1.9 < \eta < 4.9$

diffractive

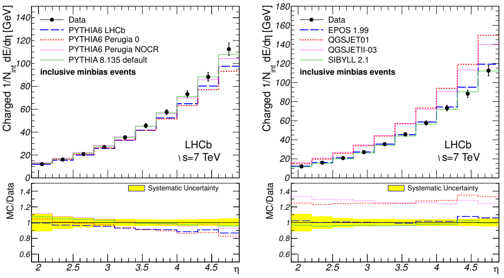
- no track with $-3.5 < \eta < -1.5$
- $\approx 70\%$ purity with PYTHIA 6

non-diffractive

- track with $-3.5 < \eta < -1.5$
- $\approx 90\%$ purity with PYTHIA 6

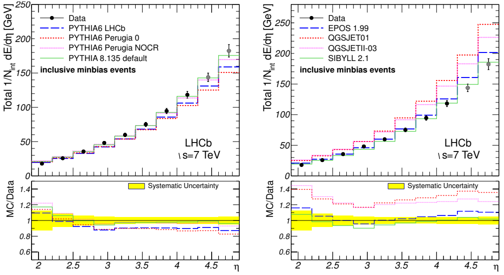
Inclusive Results

[Eur. Phys. J. C 73 (2013) 2421]



charged

- PYTHIA 8 and 6 with no CR model data well
- PYTHIA 6 under-estimates for large η
- EPOS and SIBYLL model data well
- QGSJET uniformly over-estimates

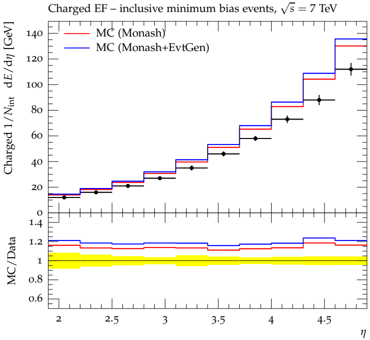


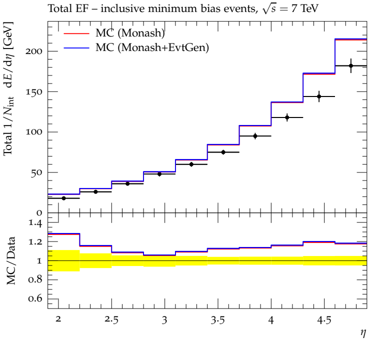
total

- similar behavior to charged energy flow

Inclusive Monash

[A. Grecu]



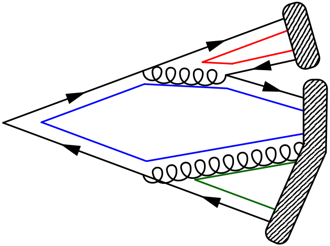


- slight overestimate of energy flow, not dependent on decays

Charge Multiplicity

Hadronization Models

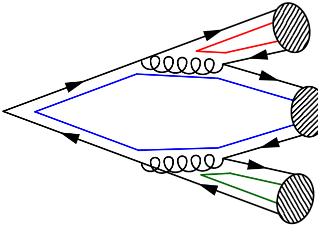
string model (PYTHIA)	cluster model (HERWIG)



- linear confinement

$$V \approx \kappa r - \frac{4\alpha_s}{3r}$$

- **split strings into hadrons**
- kinematics well modeled
- poor final state flavor description



- pre-confinement
  - clusters independent of hard process scale
  - dependent on QCD and shower scale
- **decay clusters into hadrons**
- kinematics not as well modeled
- better final state flavor description

LHCb Multiplicity Analysis

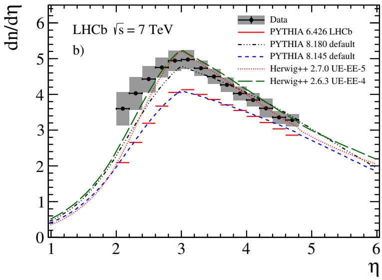
[Eur. Phys. J. C 74 (2014) 2888]

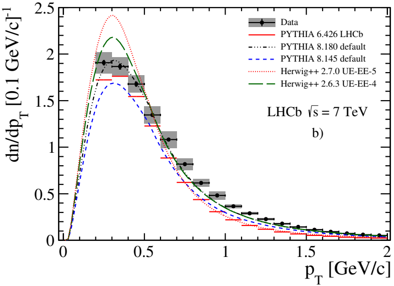
- visible event
  - at least one charged particle
  - $2.0 < \eta < 4.8$
  - $p_{\mathrm{T}} > 0.2$ GeV
  - $p > 2$ GeV
  - $\tau < 10$ ps
- reconstructed event
  - at least one track
  - must traverse all tracking stations
  - pass within 2 mm of beamline
  - originate from luminous region

1. correct for sample impurity
   - $\approx 6.5\%$ fakes, $\approx 1\%$ duplicates, $\approx 4.5\%$ non-prompt
2. account for visible events with no reconstructed tracks
3. unfold distribution for pile-up effects
4. apply reconstruction efficiencies

Density Results

[Eur. Phys. J. C 74 (2014) 2888]

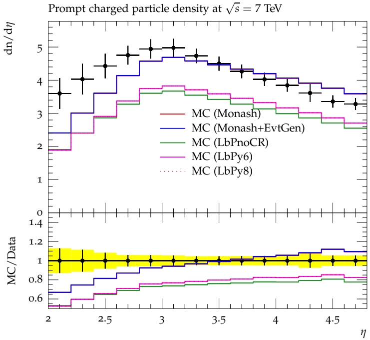


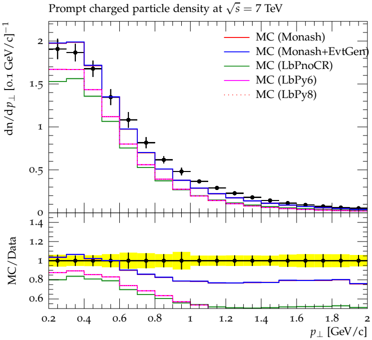


- the p requirement causes the falling distribution at low η
- neither PYTHIA 6 nor PYTHIA 8.145 were tuned with LHC data
  - these significantly under-estimate the data
- PYTHIA 8.180 describes the data well
- HERWIG++ does as well, except for $0.2 < p_{\mathrm{T}} < 0.5$

Density Monash

[A. Grecu]

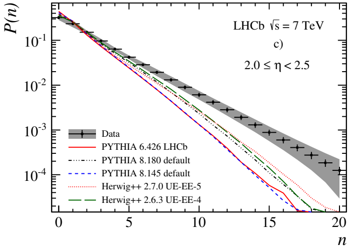


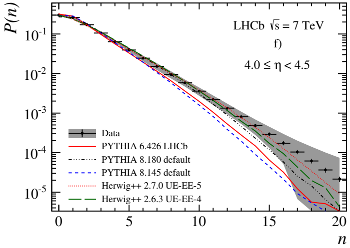


- Monash density in better agreement

Multiplicity Results

[Eur. Phys. J. C 74 (2014) 2888]

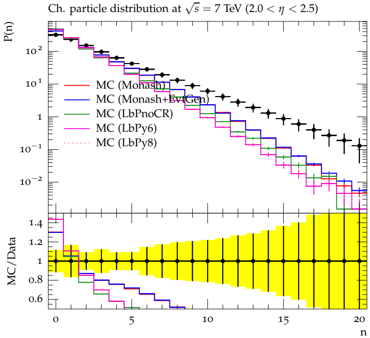


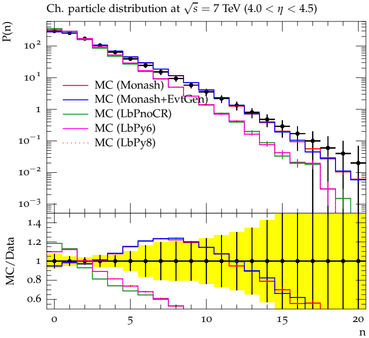


- distributions for $2.0 < \eta < 2.5$ and $4.0 < \eta < 4.5$
  - inclusive, differential p_{T}, and differential η distributions in appendix
- at low and high η all tunes under-estimate for high multiplicity
  - LHC tunes do slightly better
  - non-LHC tunes typically over-estimate low multiplicity
- inclusively PYTHIA 8.180 describes data well, but under-estimates for high multiplicity
- HERWIG++ 2.6.3 consistently describes inclusive data well
- HERWIG++ 2.7.0 does not model the range $15 < n < 25$ well

Multiplicity Monash

[A. Grecu]



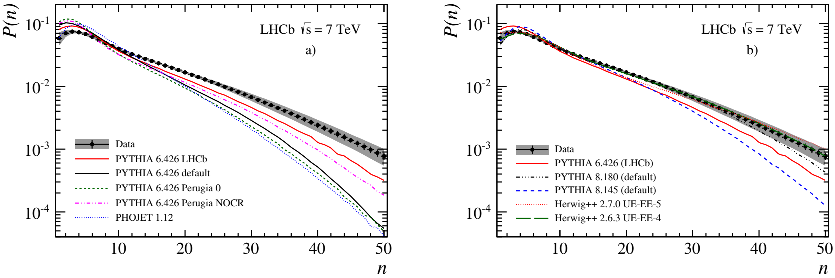


- Monash multiplicity in better agreement

Conclusions

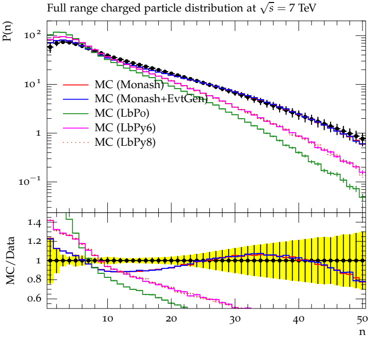
- large potential for tuning from LHCb
  - onia sector
  - forward flavor composition
  - forward soft QCD
- validates consistency of the MPI and hadronization models at LHC energies for forward production
- no unexpected behavior
- non-LHC tunes underestimate forward particle density
- Pythia 4C performs well, Monash tune does better
- Herwig++ UE-EE-4 tune consistently out-performs UE-EE-5
- some more 13 TeV results underway

Inclusive Multiplicity Results

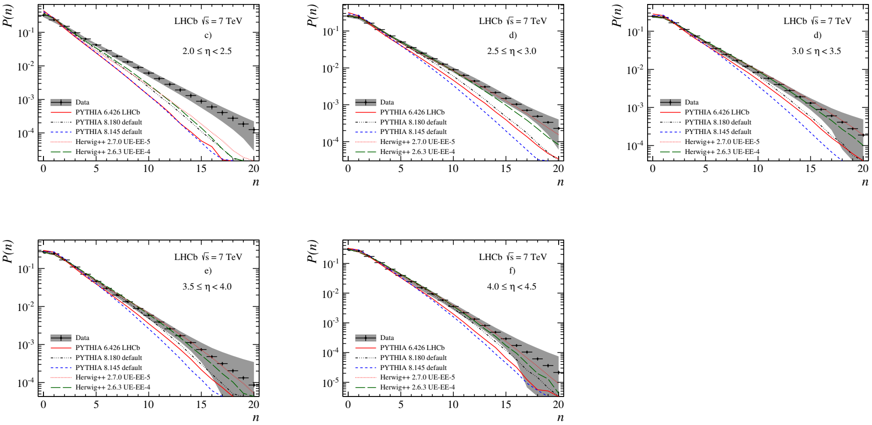


Inclusive Monash

[A. Grecu]

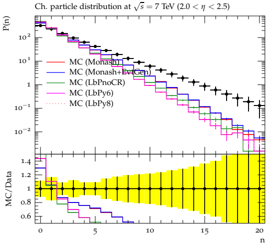


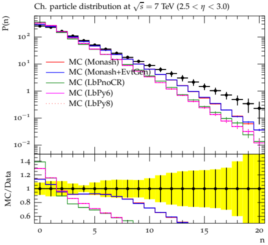
Differential Multiplicity Results (η)

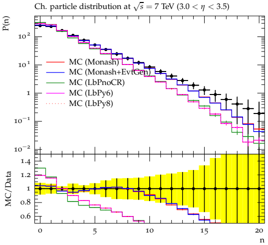


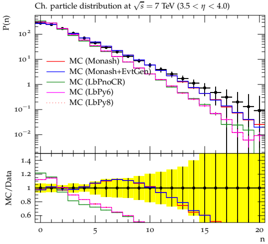
Monash (η)

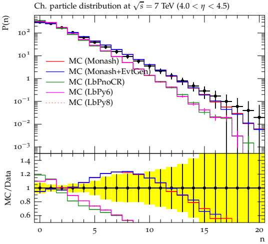
[A. Grecu]



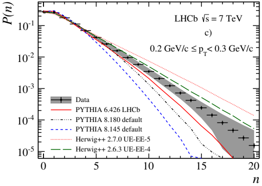


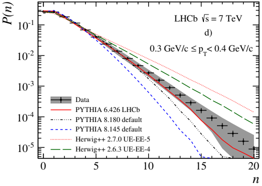


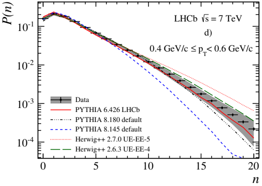


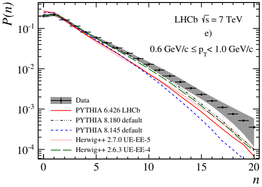


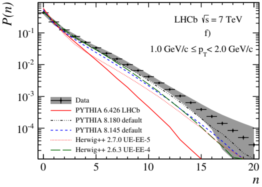
Differential Multiplicity Results (p_T)





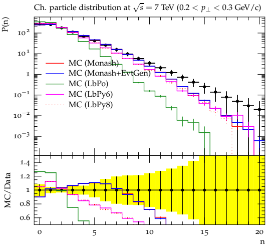


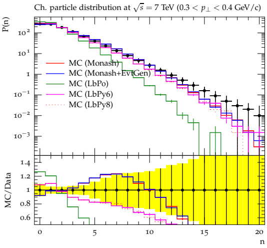


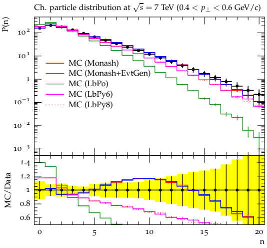


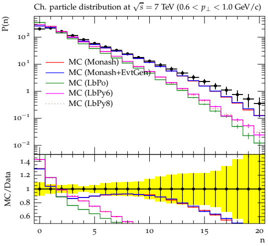
Monash (p_T)

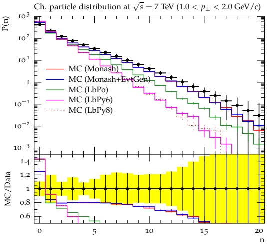
[A. Grecu]





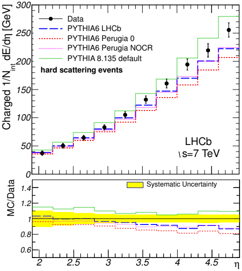


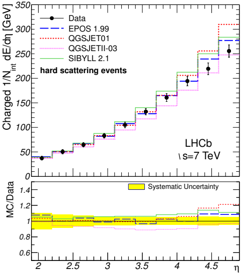




Energy Flow Hard Scatter

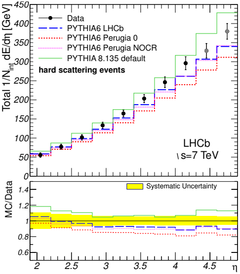
[Eur. Phys. J. C 73 (2013) 2421]

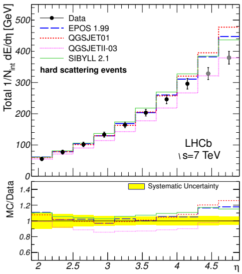




charged

- PYTHIA 8 uniformly over-estimates
- PYTHIA 6 under-estimates for large η
- EPOS, QGSJET01, and SIBYLL over-estimate for large η
- QGSJETII-03 under-estimates at middle η



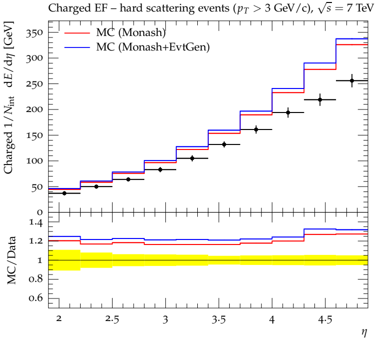


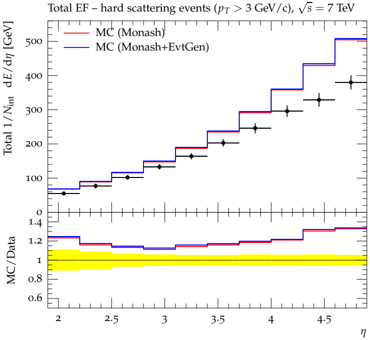
total

- similar behavior to charged energy flow

Hard Scatter Monash

[A. Grecu]





Energy Flow Diffractive

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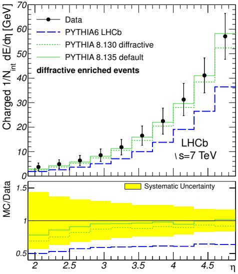
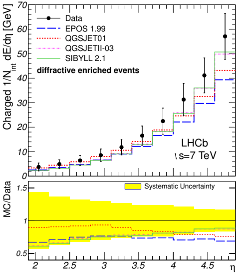
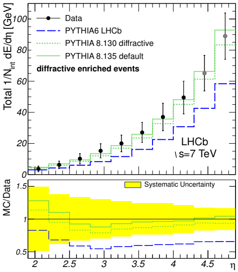
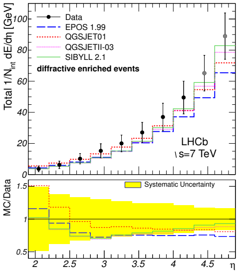




charged

- larger systematic from detector effects and magnet polarity
- PYTHIA 8 models data well
- PYTHIA 6 significantly under-estimates
- remaining generators under-estimate



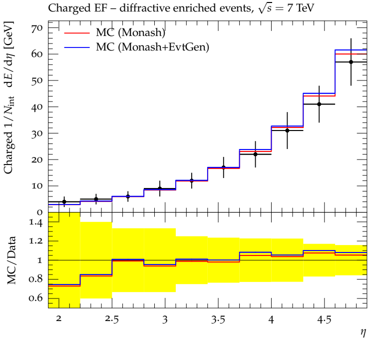


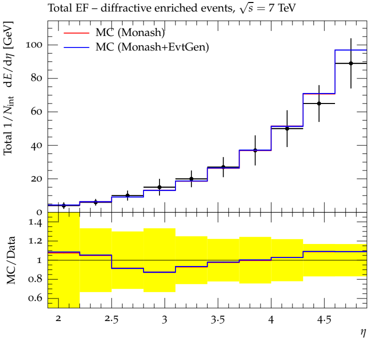
total

- similar behavior to charged energy flow for PYTHIA
- remaining generators more consistent with data
- EPOS and QGSJET01 under-estimate at high η

Diffractive Monash

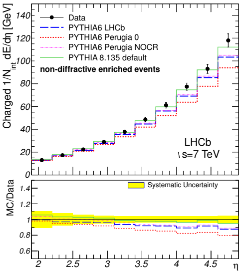
[A. Grecu]

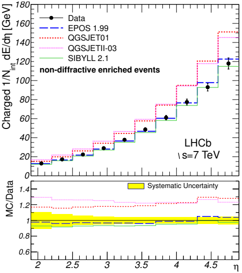




Energy Flow Non-diffractive

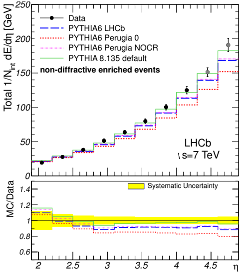
[Eur. Phys. J. C 73 (2013) 2421]

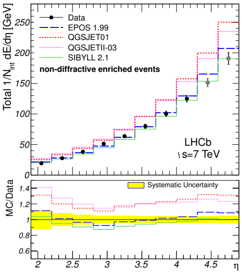




charged

- similar to inclusive results
- PYTHIA 8 models data well
- EPOS and SIBYLL also model data well





total

- similar behavior to charged energy flow

Non-diffractive Monash

[A. Grecu]